A Decision Support System for resilience based on functionality analysis of interconnected systems

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ABSTRACT

The increasing number of disruptions to Critical Infrastructure, like natural disasters, terrorist attacks, or internal failure is today a major problem of society. Concern is even greater when considering the interconnected nature of Critical Infrastructure, which might lead to failure propagation, causing domino and cascade effects. To mitigate such outcomes, critical infrastructure must recover its capacity to function with regard to several criteria. Stakeholders must therefore analyse and improve the resilience of critical infrastructure before any disruption occurs, and base this analysis on different models so as to guarantee society's vital needs. Current resilience assessment methods are mainly oriented towards the context of a single system, thus narrowing their criteria metrics, limiting flexibility and adaptation to other contexts, and overlooking the interconnected nature of systems. This article introduces a new Decision Support System that makes it possible to define a model to evaluate the functionalities of interconnected systems. The model is then used to assess the resilience of these systems based on simple and generic criteria that can be extended and adapted.

Keywords: Resilience; Functionality evaluation; Resilience assessment; Risk, Decision; Criteria; Simulation, Critical Infrastructure, System

INTRODUCTION

Modern society relies on the functioning and mutual exchange of services of various interconnected and interdependent infrastructures, i.e., systems or systems of systems (healthcare, energy, transport, manufacturing, financial, etc.) [1], [2]. The interdependencies between and within systems make them less resilient to disruptions [3]. Specifically, a disruption in an interconnected system can lead to domino and cascade effect that impacts on the other systems related to the initially affected one [4]. This becomes a problem when considering the currently increasing number of natural disasters. For instance, in July 2012, the largest blackout in history affected more than 600 million people in India. Through a cascade effect, several other systems (transport, telecommunication, finance…) also failed [5], [6]. In 2011, the flooding in South-East Asia led to a lack of hard drives and to an increase in the price of these devices all over the world [7]. The growing number of hurricanes - Sandy, Isabel, Harvey and Irma - has provoked not only human and material damage, but also economic and production/service capacity failures [8].

The notion of resilience is related to the functioning of critical infrastructures or systems and is here defined as "the capacity of a system to recover, in a minimum time, with minimum costs (financial, human, workload, etc.) a certain functioning capacity on all dimensions of its performances". Some aspects of the resilience of a system can be assessed by analysing its functionalities in several situations: (a) before a disruptive event, (b) during a disruptive event and (c) after a disruptive event. During each situation, it is important to (i) be able to assess the resilience at a given timestamp and/or period, including during disruptive events, and (ii) to identify preventive actions for different scenarios, to improve the results of the resilience assessment.

This paper focuses on situation (a) and proposes a Decision Support System for continuous and multidimensional resilience assessment based on analysis of the functionalities of interconnected systems.

Current resilience assessment approaches are oriented towards individual systems [9], whether they be financial, healthcare or transport systems. These approaches are therefore inflexible (difficult to adapt to other domains), with fixed criteria that generally concern performance (other criteria that might be important in the assessment of resilience are overlooked) and not applicable in the context of interconnected systems. This paper defines Decision Support System that makes it possible to define a model to evaluate the functionalities of interconnected systems that are linked to some aspects of resilience. The model is further used to assess resilience, based on several criteria. The proposed generic criteria can easily be extended and adapted depending on the context and needs. The originality of the approach lies in (1) the combination of functionality-analysis models and continuous resilience assessment following several dimensions of systems, (2) flexibility of criteria metrics for easy adaptation in different contexts and (3) the possibility to aggregate the results of several functionality-analysis models with continuous assessment of the resilience of interconnected systems.

The paper is organized as follows. The contribution is presented in the second section and illustrated in the third section by a case study, before concluding in the last section by an evaluation of the limits and perspectives of the research work.

Proposal

The main concepts of the proposal are illustrated in Figure 3. A system can be composed of several components. A territory can hosts several systems. The relations between systems might be functional or non-functional. Functional relations allow the circulation of flows. Non-functional relations refer to influence relations described by [10]. A component is characterized by several criteria. A criterion is defined by a value and a unit. To consider uncertainty, in normal functioning, a criterion value is comprised between a minimum value f_{min}^{n} and a maximum one f_{max}^{n}. The value of a criterion must not be outside the limits f_{max} and f_{min}. Criteria and Systems are composable (i.e., contain other criteria or systems). An evolution function defines a behaviour to simulate the evolution of a criterion and to change its value over time. The aggregation function, as its name suggests, aggregates the values of at least two criteria. The influence function determines how a given criterion/system changes another one under specified conditions. Note that feared events and flows are also instances of the concept System (see Figure 1).

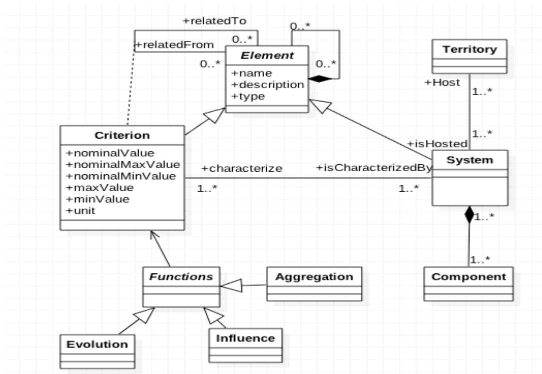

Figure 1. Conceptual model.

A functionality evaluation process defines a Functionality Evaluation Model that is further used for resilience assessment. This process is based on three steps: 1) modelling, 2) model transformation and 3) simulation. Step 1 – modelling consists of identifying systems, criteria, evolution, aggregation and influence functions. After that, relevant criteria characterizing the system are also identified. Then a function that manages every criterion is defined if needed. From a technical point of view, the modelling of these concepts is done in the Obeo Designer environment (https://www.obeodesigner.com/en). Step 2 – model transformation is an automated process that transforms designed models into a simulation environment. Technically, a model-to-text transformation script is written in Obeo Aceleo to perform the transformation from Obeo Designer to the GAMA platform. This transformation is based on [11] and [12]. Step 3 – simulation consists of simulating the results of the model transformation and plotting the result (i.e., a functionality curve). This is technically provided through the GAMA multi-agent simulation platform (http://gama-platform.org/).

This proposal is included in the framework of the MAIIEUTIC project (http://maiieutic.mines-ales.fr/) founded by the CARNOT M.I.N.E.S institute. The validation process includes several meetings with experts from System Engineering, Crisis Management, Risk Management and Multi-criteria Decision-Making approaches.

Throughout this paper, assertions 1 to 10 below define some aspects of the Functionality Evaluation Model related to resilience assessment.

- Assertion (1): Several elementary independent criteria that characterize a system can be used to define a Functionality Evaluation Model as a parameter to assess a particular aspect of the resilience of this system.

- Assertion (2): A Functionality Evaluation Model must consider the objectives and constraints of the Territory.

- Assertion (3): The value of the assessed resilience is between 0 (not resilient at all) and 1 (fully resilient).

- Assertion (4): The value of assessed resilience of a system depends on the value of each criterion aggregated into the Functionality Evaluation Model.

Assertion (5): Based on the Functionality Evaluation Model, the value of a given criterion must not be greater than certain values.

- Assertion (6): Based on the Functionality Evaluation Model, the value of a given criterion must be between certain values.

Assertion (7): There is a decrease in the value of assessed resilience due to the value of the criteria dropping out of the limits f_{min}^{n} and f_{max}^{n}.

Assertion (8): Based on a Functionality Evaluation Model, the closer the value of criteria is to the limit f_{max} or f_{min} the lower the value of assessed resilience is.

Assertion (9): Based on a Functionality Evaluation Model, if the value of a criterion is between f_{min} and f_{min}^{n} or f_{max} and f_{max}^{n} (this situation is denoted as "the system stays in a bad functioning period") for more than a given period, then the value of assessed resilience decreases.

Assertion (10): The more often the value of a criterion goes outside of f_{min}^{n} and f_{max}^{n}, the lower the value of the assessed resilience is.

Case study

The proposed methodology is applied to a simple case study. The aim here is to demonstrate the claims of the proposal. The system considered here is a network of infrastructures composed of: (1) a coal power plant, (2) a road (transport system), and (3) a signalling system. The power plant produces a certain quantity of electricity and needs trucks to deliver coal. The amount of electricity depends on the overall production capacity and the quantity of coal in incoming trucks (i.e., the quantity of transported coal). The performance of the signalling system depends on the electricity used. A bad performance impacts the safety of the road that furthermore influences the number of trucks in circulation (i.e., the quantity of transported coal to produce electricity). Therefore, a decreasing number of trucks decreases the electricity production of the power plant. Figure 2 shows the relationship between the criteria of these systems, where the arrows represent the dependence relationship.

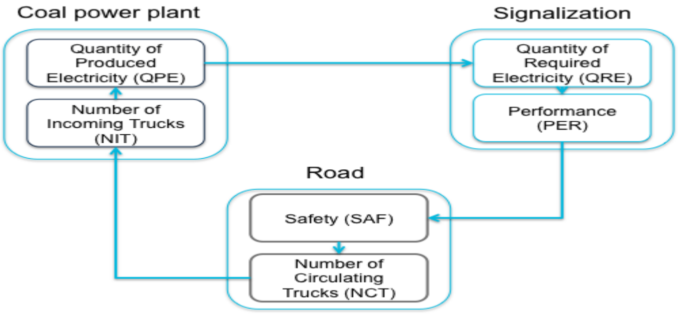

Figure 2. A use case based on a network of infrastructures.

This example is modelled using the Obeo Designer platform, transformed based on an Acceleo transformation script and simulated based on the multi-agent platform GAMA. The focus here is on the simulation results.

There are six criteria: The Quantity of Produced Electricity (QPE), the Number of Incoming Trucks (NIT), the Quantity of Required Electricity (QRE), the Performance (PER), the Safety (SAF) and the Number of Circulating Trucks (NCT). These criteria characterize the global system, as shown in the Figure 7. The proposal complies with Assertions 1 to 4; 6, defined in the previous section. For the sake of space and simplicity, only the Quantity of Produced Electricity (QPE) criterion is discussed hereafter. The objective of the power plant, assumed for this case study, is the production of 5.0 units (e.g., gigawatts); authorized minimum and maximum are assumed to be respectively 0.1 and 10. Note that Figure 3 defines the metamodel for these parameters. In normal functioning, the fluctuation might be between [3.0 - 7.0]. 5 units are tolerated if the objective is not fulfilled. The evolution function for the QPE, i.e., $f_n(t)$ is defined below.

$$f_n(0) = 5.0$$
$$f_n(t+1) = f_n(t) \pm \rho(0.5) \quad (1)$$

Where $\rho(x)$ is a random function that for a given number x returns a random number n such that $0 \leq n \leq x$.

In addition, the value of f_{min}^n, f_{max}^n, f_{min} and f_{max} should change with respect to time. For instance, the power consumption of a city depends on seasons (e.g., electricity consumption increases during winter) and thus the minimal production of the power plant should be greater than 3.0. Consequently, the evolution functions defined by Equation (25 – 28) are assigned to f_{min}^n, f_{max}^n, f_{min} and f_{max}. Note that for the sake of simplicity, these functions randomly change the value of their parameters.

$$f_{min}(0) = 0.1$$
$$f_{min}(t+1) = f_{min}(t) \pm \rho(0.1) \quad (2)$$

$$f_{max}(0) = 10$$
$$f_{max}(t+1) = f_{max}(t) \pm \rho(0.1) \quad (3)$$

$$f_{min}^n(0) = 3.0$$
$$f_{min}^n(t+1) = f_{min}^n(t) \pm \rho(0.1) \quad (4)$$

$$f_{max}^{n}(0) = 7.0$$
$$f_{max}^{n}(t+1) = f_{max}^{n}(t) \pm \rho(0.1) \quad (5)$$

For all situations the value of assessed resilience is between 0 and 1 and depends on all six criteria. However, there is no constraint on the duration of the bad functioning periods, and consequently, Assertions 9 and 10 are not tested in this use case. For the other assertions, i.e., Assertions 5; 7 and 8, two simulations are proposed: one for the up value, and one for the down value. For each assertion, the simulation result shown here is for 12 timestamps. For example, the Figure 8 illustrates a disruptive event that causes a drop-up (overload) of the QPE that cannot be mitigated and causes a system crash. Resilience factor R_{C0}^{up} remains 1 while the value of the criteria is superior to f_{min} or inferior to f_{max}, until the disruptive event occurs at timestamp 9 (Figure 8). After timestamp 9, a drop-up of the QPE causes the system to enter a bad functioning period. Shortly after, i.e., just before timestamp 10, the system enters an unacceptable state because the QPE becomes superior to f_{max} and R_{C0}^{up} becomes 0

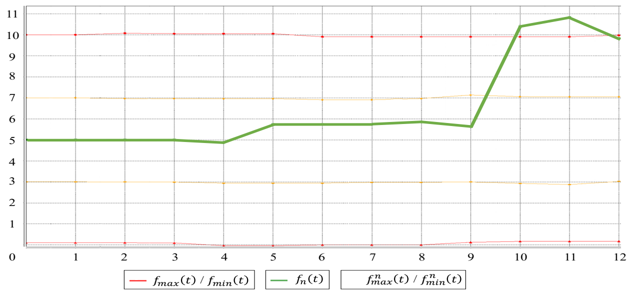

Figure 8: Simulation

Conlusion

Infrastructures are nowadays facing an increasing number of disruptions, from natural disasters to terrorist attacks and internal failures. Mitigating these negative effects means that the infrastructures must recover their initial functioning capacity in minimum time, with minimum costs, i.e., they must be resilient. Thus, stakeholders must analyse the resilience of infrastructures before any disruption to anticipate the right decisions at the right time. This paper introduces a Decision Support System for the evaluation of the functionality of interconnected systems for the purpose of resilience assessment. The methodology is designed to prepare Stakeholders for different disruptions before they happen, allowing them to make the right decisions at the right time. The major contributions of the methodology are:

- It provides a relevant tool for the combination of functionality analysis models and continuous resilience assessment following several dimensions of systems;
- It proposes a way to connect rough data with functional analysis and resilience assessment;
- It proposes an agile, evolutive and continuous resilience assessment paradigm (it can be extended with other criteria, other data sources to define criteria, other aggregation formulas, etc.).

The main limitation of the approach is its dependence on relevant input data. In other words, an incorrect domain knowledge as input will surely provide an incorrect evaluation. In this sense, we are unable to warn users about the inconsistency of their input data.

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